DIRECT USE OF A MESFET PHYSICAL MODEL IN NON-LINEAR CAD

Paulo J. C. Rodrigues, Michael J. Howes+, and John R. Richardson+*

**Universidade de Brasília - Departamento de Engenharia Elétrica*
Caixa Postal 04591, Brasília - DF - 70.919 - Brazil
+University of Leeds - Department of Electronic & Electrical Engineering
Leeds, LS2 9JT - U.K.

ABSTRACT

This work presents a CAD tool which combines a novel quasi-two-dimensional MESFET physical model with an efficient non-linear circuit analysis technique. Device technological parameters (dimensions, doping profile, etc.) can be directly related to electrical performance with this tool which can therefore be used in non-linear circuit yield study and optimization. An excellent agreement between simulated and measured results was obtained.

1. INTRODUCTION

The availability of CAD tools which directly relate technological parameters to electrical performance is highly desirable in a MMIC environment where yield is a main concern. Equivalent-circuit models cannot address this problem properly as they rely on measured data of existing devices. In contrast, besides relating technology to electrical performance, physical models can simulate devices even before they are manufactured. The main difficulty in using physical models has been to achieve a good compromise between accuracy and speed so that they can be used extensively.

MESFET physical models have been used in two ways in non-linear CAD. In the first approach, quasi-two-dimensional models have been used directly [1],[2]. However, the models used are not suitable for general nonlinear CAD as they cannot handle the current reversals which occur near the pinch-off region. This is because, in those models, the device equations are solved as an initial-value problem in space and therefore become unstable when current reversals take place [3]. The second approach consists of using either quasi-two-dimensional [4] or two-dimensional [5],[6] physical models to generate equivalent-circuit models. This undoubtedly results in a much faster model but, besides relying on the quasi-static approximation, it has problems with respect to the definition and computation of the equivalent-circuit elements, mainly the capacitances.

In the quasi-two-dimensional model described in this work, the device equations are solved as a boundary-value problem in space. This approach has two main advantages: the resulting model is suitable for general non-linear CAD and no term has to be removed from the equations. In the initial-value approach, carrier diffusion must be removed to ensure stability even if the accuracy of the model is degraded. Although quasi-two-dimensional models are between two and three orders of magnitude faster than two-dimensional models, they are still very slow when compared to equivalent-circuit models. Therefore, particular attention was paid to the numerical efficiency of the model and of the nonlinear circuit analysis method used. The resulting CAD tool is shown to provide an excellent agreement with measured results and an example of its use in yield analysis is given.

2. THE NOVEL QUASI-TWO-DIMENSIONAL MESFET PHYSICAL MODEL

A novel quasi-two-dimensional MESFET physical model which is suitable for general non-linear CAD was developed. First, a single-gas model which correctly accounts for the two-valley structure of GaAs was derived [3]. One-dimensional equations were then obtained on a curvilinear coordinate (β) in the direction of the current flow using a procedure similar to that described in [7]. Errors in the equations of that reference were corrected for and further simplifying assumptions were introduced to achieve a faster model. The resulting device equations were

$$\frac{\partial}{\partial\beta}\left(Y\frac{\partial\phi}{\partial\beta}\right) = \frac{q}{\epsilon_S}(\bar{n} - \bar{N}) \tag{1}$$

$$\frac{\partial\bar{n}}{\partial t} + \frac{\partial}{\partial\beta}(\bar{n}v_\beta) = \bar{G} - \frac{J_g}{q} \tag{2}$$

$$\frac{\partial}{\partial t}(m\bar{n}v_\beta) + \frac{\partial}{\partial\beta}(m\bar{n}v_\beta^2) = \bar{n}\frac{\partial\phi}{\partial\beta} - \frac{\partial}{\partial\beta}(\bar{n}T) + \bar{n}T\frac{\partial}{\partial\beta}\ln(Y) - \frac{m\bar{n}v_\beta}{\tau_p} + mv_\beta(\bar{G} - \frac{J_g}{q}) \tag{3}$$

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$$\frac{\partial}{\partial t}(\bar{n}w) + \frac{\partial}{\partial \beta}(\bar{n}v_\beta w) = \bar{n}v_\beta \frac{\partial \phi}{\partial \beta} - \frac{\partial}{\partial \beta}(\bar{n}v_\beta T) + \frac{\partial}{\partial \beta}\left(\bar{\kappa}\frac{\partial T}{\partial \beta}\right) + w\bar{G} - \frac{J_g}{q}(w + T) - \bar{n}\frac{w - w_0}{\tau_w} \tag{4}$$

where Y is the channel opening (Fig. 1), ϕ the electric potential, q the electronic charge, ϵ_s the dielectric constant, $\bar{n}$ the sheet electron density, $\bar{N}$ the sheet donor density in the active channel, t the time, v_β the electron velocity in the β direction, $\bar{G}$ the carrier generation term due to avalanche ionization, J_g the gate forward conduction current density, m the electron mass divided by q, T the electron temperature in eV, τ_p the momentum relaxation time, w the electron energy in eV, $\bar{\kappa}$ the sheet thermal conductivity, w_0 the equilibrium energy, and τ_w the energy relaxation time. Equations (1)-(4) represent respectively Poisson's equation, particle conservation, momentum conservation, and energy conservation. These equations form an incompletely parabolic problem similar to those which appear in Fluid Dynamics [3]. This fact has a great impact on their discretization and solution. The "sound speed" of the electron gas can be calculated as

$$c = \sqrt{\frac{T}{m}} \tag{5}$$

and, since supersonic flow ($|v_\beta|>c$) occurs in GaAs even at room temperature, discretization schemes which can handle discontinuous solutions and supersonic flow have to be used. In this model, a conservative upwind finite-volume scheme was adopted. The discretized equations are solved as a boundary-value problem and this is efficiently done using Newton's method and taking advantage of the block-diagonal structure of the Jacobian.

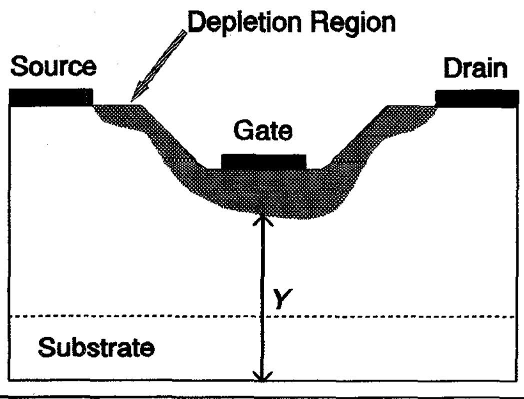

Figure 1: FET geometry.

The model can simulate real nonuniform doping profiles (previous quasi-two-dimensional models could only simulate uniform doping profiles) and accounts for phenomena such as velocity overshoot, electron heating, and surface states. Further details can be found in reference [3].

3. NON-LINEAR CIRCUIT ANALYSIS

The non-linear circuit analysis is carried out using the Convolution-Based Sample-Balance technique [8],[9]. Although this is a frequency-domain technique, the circuit equations are formulated in terms of time-domain variables. As a consequence, the interface with the physical model is simplified. The resulting system of non-linear algebraic equations has the form

$$\boldsymbol{F}(\boldsymbol{x}) = \boldsymbol{y}.\boldsymbol{v}(\boldsymbol{x}) + \boldsymbol{i}(\boldsymbol{x}) - \boldsymbol{u} = \boldsymbol{0} \tag{6}$$

where $\boldsymbol{x}$, $\boldsymbol{v}$, $\boldsymbol{i}$, and $\boldsymbol{u}$ are vectors respectively of non-linear subcircuit controlling variables, non-linear subcircuit port voltages, non-linear subcircuit port currents and linear subcircuit Norton current sources at equally spaced time instants and y is a matrix related to the Y-matrix of the linear subcircuit. This system is solved using an algorithm based on a quasi-Newton method [10] which has been shown to be up to nearly an order of magnitude more efficient than Newton's method. This is particularly important in this case since most of the CPU time is spent simulating the physical model. When needed, the Jacobian is computed numerically using the scheme discussed in [10] (analytical computation of the Jacobian when a physical model is used is a formidable task).

4. COMPARISON BETWEEN SIMULATED AND MEASURED RESULTS

Fig. 2 shows simulated and measured DC characteristics for a 0.5 μm gate power MESFET. Other than for the recess depth, nominal dimensions provided by the device manufacturer were used in the simulation. The recess depth was changed by less than 5% in order to match the saturation current (I_{dss}). The need for this adjustment is not surprising in view of the spreading in pinch-off voltages and saturation currents of commercial FETs. The agreement obtained was excellent.

The device was then biased as a pinch-off multiplier and measured on a 50 Ω system for an input frequency of 4 GHz. For the parasitic circuit elements, which are not accounted for in the physical model, values provided by the manufacturer were used. Simulated and measured results are displayed in Figs. 3-5 respectively for DC, second and third harmonics. Overall agreement is excellent, specially considering all uncertainties involved. The total CPU time required for the simulation was 2400 s on an Amdahl V7 computer which is somewhat slower than several modern workstations. A huge increase in CPU time would be expected if Newton's method were used in the non-linear circuit analysis.

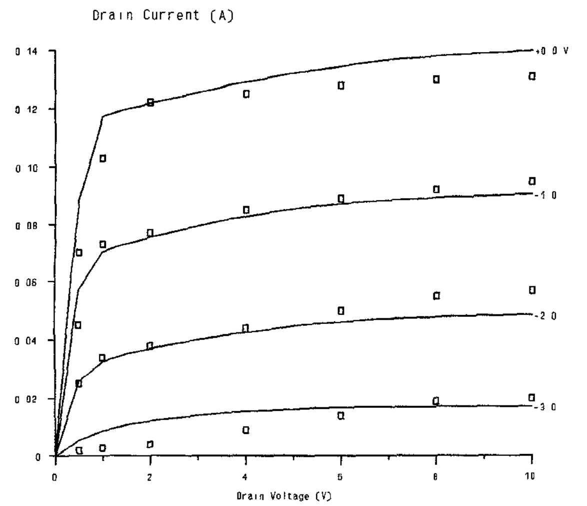

Figure 2: Simulated (solid lines) and measured (squares) DC characteristics of a 0.5 μm gate FET.

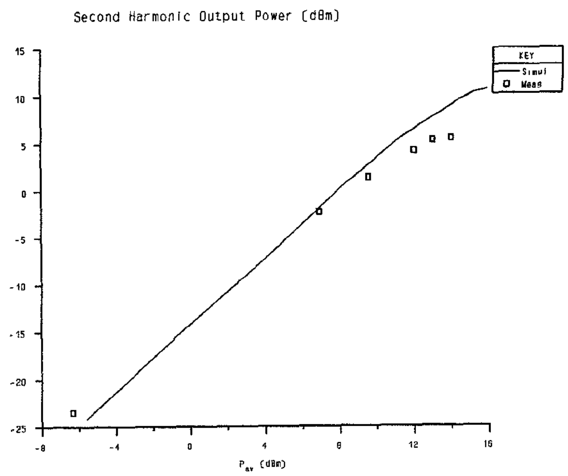

Figure 4: Measured (squares) and simulated (solid line) output power at the second harmonic versus power available from the source for the FET biased as a pinch-off multiplier.

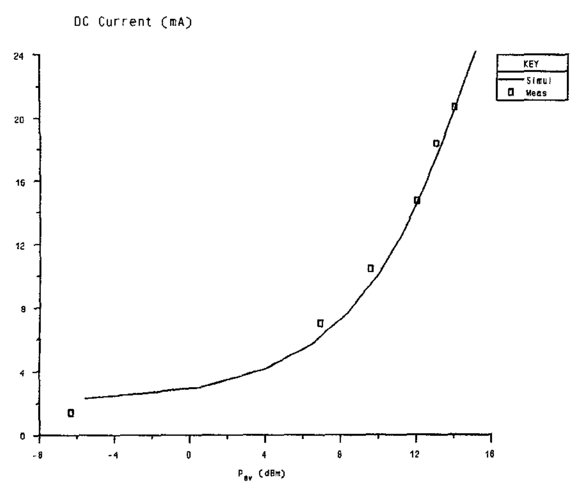

Figure 3: Measured (squares) and simulated (solid line) drain current versus power available from the source for the FET biased as a pinch-off multiplier.

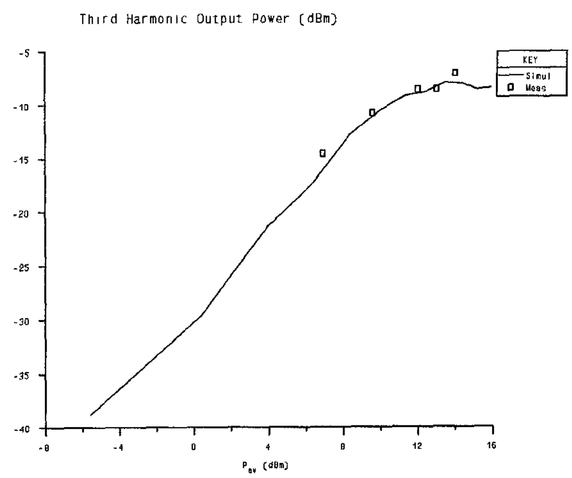

Figure 5: Measured (squares) and simulated (solid line) output power at third harmonic versus power available from the source for the FET biased as a pinch-off multiplier.

5. EXAMPLE OF APPLICATION

A frequency doubler was designed using the 0.5 μm gate power MESFET. Simulated results are shown in Fig. 6. The doping profile was then decreased by 15% and the recess depth adjusted to achieve the same I_{dss}, as is done in several processing technologies. The modified device was then simulated and its results are also shown in Fig. 6. The modifications in the MESFET reduced the non-saturated gain since matching was degraded but the maximum power is virtually the same in both cases. Since multipliers usually operate at saturation, this means that the output power at the second harmonic and the conversion gain are highly insensitive to the doping profile level if the devices have the same I_{dss}.

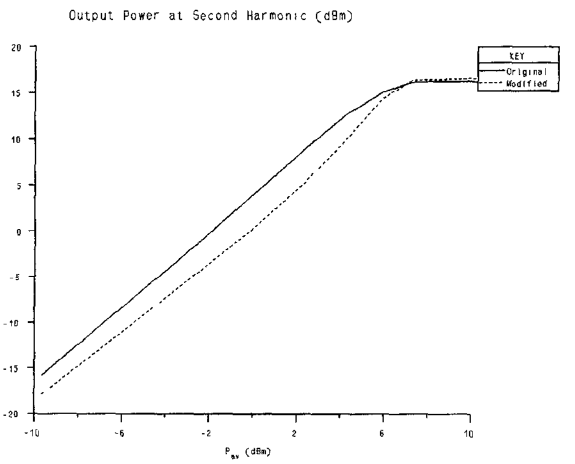

Figure 6: Second harmonic output power as a function of the power available from the source: original FET (solid line) and modified FET (broken line).

6. CONCLUSIONS

A CAD tool which is suitable for non-linear circuit yield study and optimization in a MMIC environment has been presented. It has been shown to be accurate, flexible and to require only reasonable amounts of CPU time. This tool should therefore be useful in helping the MMIC designer to obtain high yield non-linear circuits with reduced costs.

ACKNOWLEDGEMENT

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